INTRODUCTION

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1.1 Well logs – a definition

The continuous recording of a geophysical parameter along a borehole produces a geophysical well log. The value of the measurement is plotted continuously against depth in the well (Figure 1.1). For example, the resistivity log is a continuous plot of a formation's resistivity from the bottom of the well to the top and may represent over 4 kilometres (2½ miles) of readings.

The most appropriate name for this continuous depth-related record is a wireline geophysical well log, conveniently shortened to well log or log. It has often been called an 'electrical log' because historically the first logs were electrical measurements of electrical properties. However, the measurements are no longer simply electrical, and modern methods of data transmission do not necessarily need a wire line so the name above is recommended. This book therefore concerns wireline geophysical well logs.

In France, where well logging was first invented by Conrad Schlumberger and Henri Doll, the original name was 'Carottage Électrique' (electrical coring) as opposed to mechanical coring. Today the name *diagraphies différées* (literally, 'deferred diagrams') is applied to distinguish wireline geophysical well logs, which are made after drilling, from the drill logs (*diagraphies immédiates*, i.e. immediate diagrams) made during the drilling. In English no such distinction is made – the word 'log' is universally used.

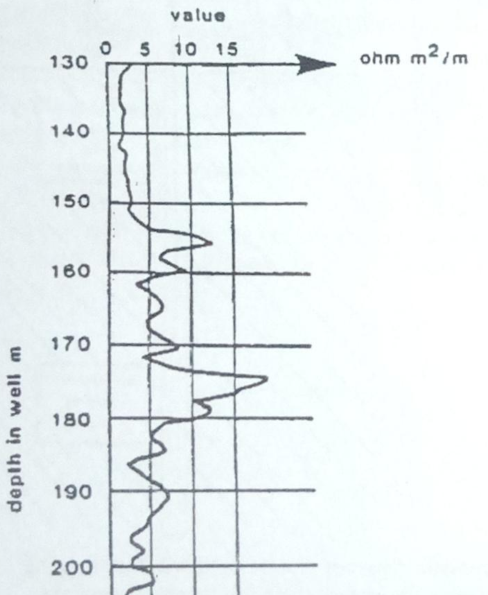

Figure 1.1 A well log. Representation of the first 'log' made at Pechelbronn, Alsace, France, in 1927 by H. Doll. (From Allaud and Martin, 1976).

1.2 Well logs – the necessity

Many different modern geophysical well logs exist. They are records of sophisticated geophysical measurements along a borehole. These may be measurements of spontaneous phenomena, such as natural radioactivity (the gamma ray log), which requires a tool consisting simply of a very sensitive radiation detector; or they may be induced, as with the formation velocity log (sonic log), in which a tool emits sound into the formation and measures the time taken for the sound to reach a receiver at a set distance along the tool (Table 1.1).

Geophysical well logging is necessary because geological sampling during drilling ('cuttings sampling') leaves a very imprecise record of the formations encountered. Entire formation samples can be brought to the surface by mechanical coring, but this is both slow and expensive. The results of coring, of course, are unequivocal. Logging is precise, but equivocal, in that it needs interpretation to bring a log to the level of geological or petrophysical experience. However, logs fill the gap between 'cuttings' and 'cores', and with experience, calibration and computers, they can almost replace cores, as they certainly contain enough information to put outcrop reality into the subsurface.

1.3 Wireline logs – the making

Wireline geophysical well logs are recorded when the drilling tools are no longer in the hole. 'Open-hole' logs, (open-hole indicates that the formation forms the wall of a well, as opposed to 'cased-hole, in which a tube of metal casing lines the well), the subject of this book, are recorded immediately after drilling. MWD

Table 1.1 Classification of the common wireline geophysical well measurements (in 'open hole').

	Log Type	Formation parameter measured
Mechanical measurements	Caliper	Hole diameter
Spontaneous measurements	Temperature	Borehole temperature
	SP (self-potential)	Spontaneous electrical currents
	Gamma ray	Natural radioactivity
Induced measurements	Resistivity	Resistance to electrical current
	Induction	Conductivity of electrical current
	Sonic	Velocity of sound propagation
	Density	Reaction to gamma ray bombardment
	Photoelectric	Reaction to gamma ray bombardment
	Neutron	Reaction to neutron bombardment

(measurement while drilling) or LWD (logging while drilling) logs, by contrast, are made as a formation is drilled. Quite different techniques are made to record MWD and LWD logs but the results are comparable to the open hole wireline logs (*see* Section 1.6).

Wireline logs are made using highly specialized equipment entirely separate from that used for drilling. Onshore, a motorized logging truck is used which brings its array of surface recorders, computers and a logging drum and cable to the drill site. Offshore, the same equipment is installed in a small cabin left permanently on the rig. Both truck and cabin use a variety of interchangeable logging tools, which are lowered into the well on the logging cable (Figure 1.2).

Most modern logs are recorded digitally. The sampling rate will normally be once every 15 cm (6 in), although for some specialized logs it will be as low as 2.5 mm (0.1 in). An average well of say 2000 m will therefore be sampled over 12 000 times for each individual log, and for a suite of 8 or so typical logs, it will be sampled over 100,000 times (although for some new, specialised tools, this can be the sampling rate per metre!). At typical logging speeds, data transmission rates will vary from 0.05 kilobits per second for simpler logs to over 200 kilobits per second for the new complex logs. The huge amount of data representing each logging run is fed into the computer of the surface unit. There is generally an instantaneous display for quality control and a full print-out immediately the log is finished, but the raw data are stored on magnetic tape for future processing and editing.

To run wireline logs, the hole is cleaned and stabilized and the drilling equipment extracted The first logging tool is then attached to the logging cable (wireline) and lowered into the hole to its maximum drilled depth. Most logs are run while pulling the tool up from the bottom of the hole. The cable attached to the tool acts both as a support for the tool and as a canal for data transmission. The outside consists of galvanized steel, while the electrical conductors are insulated in the interior (Figure 1.3). The cable is wound around a motorized drum on to which it is guided manually during logging. The drum will pull

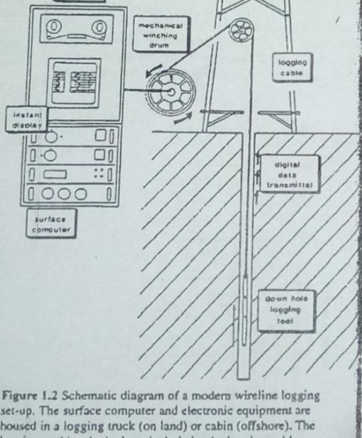

Figure 1.2 Schematic diagram of a modern wireline logging set-up. The surface computer and electronic equipment are housed in a logging truck (on land) or cabin (offshore). The logging tool is winched up the hole by the logging cable which also transmits the tool readings. The transmittal is digital and recorded on magnetic tape. The surface computer allows instant display.

the cable at speeds of between 300 m/h (1000 ft/h) and 1800 m/h (6000 ft/h), i.e. 0.3 to 1.8 km/h, depending on the tool used. As the cable is pulled in, so the depth of the working tool is checked. Logging cables have magnetic markers set at regular intervals (e.g. 100 ft or 25m) along their length and depths are checked mechanically, but apparent depths must be corrected for cable tension and elasticity.

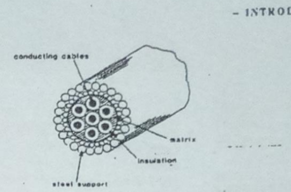

Figure 1.3 Schematic diagram of a 7 core logging cable. (Modified from Moran and Attali, 1971.)

Because rig time is expensive and holes must be logged immediately, modern logging tools are multi-function (Figure 1.4). They may be up to 28 m (90 ft) in length, but still have an overall diameter of only 3–4 in (although new, shorter tools are being prepared). The Schlumberger ISF sonic tool, for example, of 3⅜in diameter, is 55.5 ft (16.9 m) long and gives a simultaneous measurement of gamma ray or caliper, SP, deep resistivity (conductivity), shallow resistivity and sonic velocity. The complexity of such tools requires the use of the surface computer, not only to record but also to memorize and to depth-match the various readings. The gamma-ray sensor, for example, is not at the same depth as the resistivity sensors (Figure 1.4), so at any one instant, different formations are being sampled along the tool. The surface computer therefore memorizes the readings, compensates for depth or time lag and gives a depth-matched output.

Despite the use of the combined tools, the recording of a full set of logs still requires several different tool descents. While a quick, shallow logging job may only take 3–4 hours, a deep-hole, full set may take 2–3 days, each tool taking perhaps 4–5 hours to complete.

1.4 Log runs

When a log is made it is said to be 'run'. A log run is typically made at the end of each drilling phase, i.e. at the end of the drilling and before casing is put in the hole (Figure 1.5). Each specific log run is numbered, being counted from the first time that the particular log is recorded. Run 2 of the ISF Sonic, for example, may cover the same depth interval as a Formation Density Log Run 1. In this case it means that over the first interval of the ISF Sonic, (i.e. Run 1), there was no Formation Density log recorded (Figure 1.5).

Typically, through any well, more logs are run over intervals containing reservoirs or with shows, than over apparently uninteresting zones. The choice of logs depends on what it is hoped to find. Logging costing

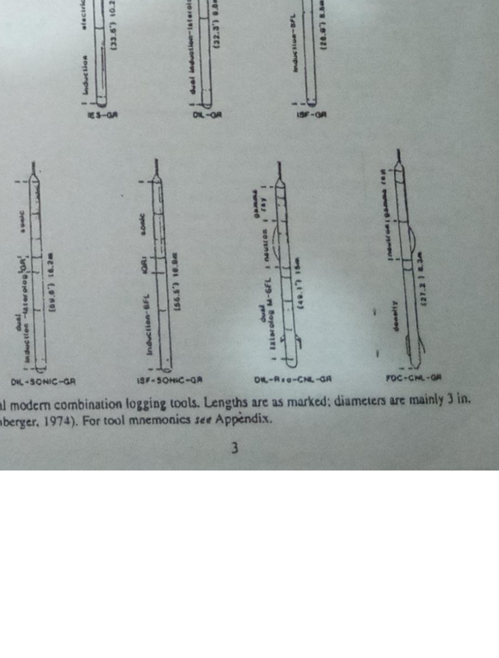

Figure 1.4 Some typical modern combination logging tools. Lengths are as marked; diameters are mainly 3 in. (Modified from Schlumberger, 1974). For tool mnemonics *see* Appendix.

5–10% of total well costs is expensive, so that in cheap, onshore wells, in known terrain, a minimum set is run. Offshore, where everything is expensive, full sets of logs are generally run, even if hydrocarbons are not found, as each well represents hard-gained information. Cutting down on well logs is probably a false economy, but it can be forgiven when prices are considered.

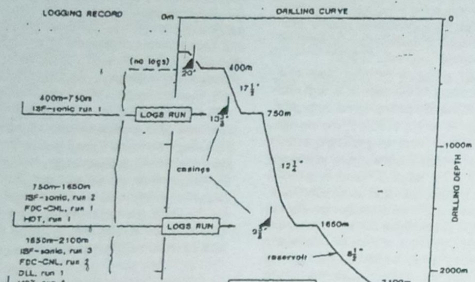

Figure 1.5 Logging record. Log runs are indicated on a typical offshore drilling curve. Horizontal lines indicate no drilling, when logs are run. Casing follows logging. Note log run numbers. (Tool mnemonics – Schlumberger, *see* Appendix).

Figure 1.6 Three typical API log formats. Tracks are 2.5in wide with a central 0.75in depth column. Overall width is 8.25in. Vertical scales are variable (*see text*).

1.5 Log presentations

A standard API (American Petroleum Institute) log format exists (Figure 1.6). The overall log width is 8.25 in (21 cm), with three tracks of 2.5 in (6.4 cm), tracks 1 and 2 being separated by a column of 0.75 in (1.9 cm) in which the depths are printed. There are various combinations of grid. Track 1 is always linear, with ten standard divisions of 0.25 in (0.64 cm). Tracks 2 and 3 may have a 4-cycle logarithmic scale, a linear scale of 20 standard divisions, or a hybrid of logarithmic scale in track 2 and linear scale in track 3 (Figure 1.6).

These are the classic presentations which, in the past, usually prevailed. With the advent of digitized logs, non-standard formats are becoming more common, especially on computer playbacks.

On the old analog logging systems, the choice of vertical or depth scales was limited to two of 1:1000, 1:500, 1:200, 1:100, 1:40 and 1:20. From these, the most frequent scale combinations were 1:500 (1cm = 5 m) for résumé or correlation logs and 1:200 (1cm = 2 m) for detailed reservoir presentation.

The American area was an exception, where the available scales were 1:1200, 1:600, 1:240 and 1:48. From these the commonly-chosen scales were 1:600 (1 in=100 feet) for résumé and correlation logs, and 1:240 (5 in = 100 feet) for detail.

These scales still dominate industry documents, but as a result of modern computer storage other scales are becoming more common. Especially useful to the geologist are the reduced scales of 1:2000 (1 cm = 20 m) and 1:5000 (1 cm = 50 m). In fact any convenient scale can now be produced easily by the computer, whereas in the past scale changes could only be made by unsatisfactory photographic methods.

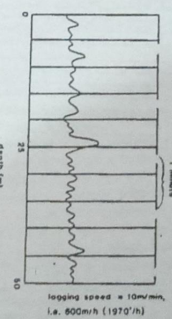

Figure 1.7 Dashed log margin representing minute intervals (Schlumberger). The logging speed can be checked from these dashes.

One final aspect of the log grid to note are markers which indicate real time during logging. On Schlumberger logs, time is indicated by the dashed grid margins on the field prints. Each dash represents one minute, regardless of log scale (Figure 1.7). Other companies use ticks or spikes on the grid for the same purpose. Time markers allow a direct control of logging speed and, indirectly, log quality.

Every log grid is preceded by a comprehensive log heading. It covers all aspects which allow the proper interpretation of the log and, in addition, identification of the well, rig, logger and logging unit. The log heading illustrated (Figure 1.8) is but one example, each company having its own format.

On the log tail is found a repetition of some of the log-head data, simply for convenience. Calibration data are also added to the log tail, as are short, doubled-up or repeat sections which act as samples for empirical quality control.

1.6 LWD Logs (*Logging while drilling)

(*MWD, Measurement While Drilling, is generally taken to refer to simpler, drilling-type measurements such as hole deviation, while LWD, Logging While Drilling, is taken to refer to log-type measurements such as resistivity, density and so on. However, there is still some confusion.)

Wireline logs are made, as has been described (Section 1.3) on a single pass of each specialized tool once drilling ceases and the bit is taken out of the hole. LWD logs, on the contrary, are built up, metre by metre, as drilling actually takes place. The technique is quite different.

An LWD tool consists of three elements: downhole logging sensors, a data transmission system and a surface interface. The logging sensors are placed just behind the drill bit in specialised drill collars (lengths of reinforced drill string) and are active in the hole during drilling. The sensor signals are transmitted to the surface, generally in digital format, by pulse telemetry through the drilling mud and collected by surface receivers. The signals are converted and a continuous log slowly built up as drilling progresses. The formation is therefore logged very soon after drilling, a matter of minutes to several hours, depending on drilling rates and the distance between the bit and the downhole sensors.

Services now offered by the LWD companies include gamma ray, resistivity, density, neutron and a continuous directional survey (a sonic is imminent). The log types are similar (but not identical) to the wireline log types of similar category. Thus a gamma ray LWD log is comparable to a wireline gamma ray log, and an LWD resistivity log is comparable to a 'shallow' wireline resistivity log. In general, the LWD logs are as accurate as the wireline logs and can be interpreted in a similar way. However, the characteristics of the readings and data quality problems are rather different.

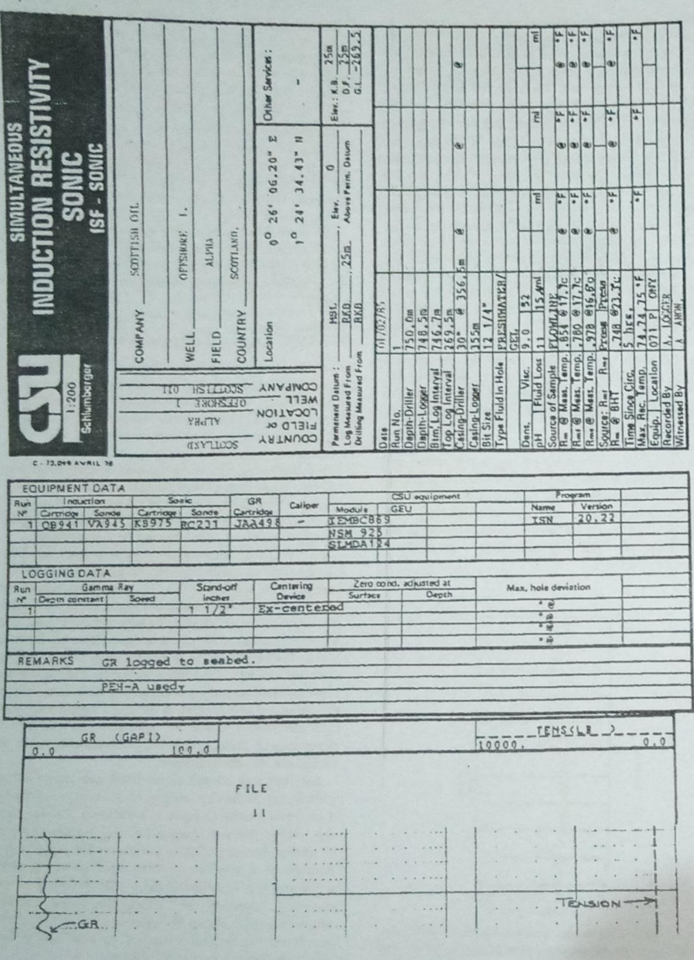

Figure 1.8 A typical log heading.

LWD tools are much used in highly deviated and horizontal wells where they help to direct the drilling and function in conditions very difficult for standard wireline tools. Also, it is found that multiple passes with the LWD tools, combined with the wireline log results, give a very accurate picture of fluid movement in the period following drilling (Chapter 6). Case studies suggest that often wireline logs are not run at the best time in terms of borehole conditions (Cunningham *et al.*, 1991).

LWD logs are clearly going to be used more and more, partly as a replacement to the open hole logs and partly as an addition, especially in horizontal or highly deviated wells (Walsgrove *et al.*, 1992). However, the interpretation of LWD logs involves problems rather specific to the LWD technique and tool types involved. At present we are still at the stage of comparing LWD with wireline logs, expecting the latter to be the 'standard'. Very soon the reverse will be true since the slower logging speed of the LWD technique offers the potential for a better reading. But, in order to keep this book at a relatively straightforward level, the LWD logs are used occasionally as examples, but are not considered further, *per se*.

1.7 The logging companies

The wireline well-logging world is dominated by one, extremely successful, giant international company – Schlumberger. In America a number of other companies exist but in many parts of the world Schlumberger has a quasi-monopoly. The reasons for this domination are partly historical: it was the frères Schlumberger, Conrad and Marcel, who created the original SPE (Société de Prospection Électrique) in 1926, the precursor of the modern Schlumberger. The brothers, along with H.G. Doll, were the creators of the well-logging technique.

The international forum is becoming more competitive, and in America smaller companies are active. However, two names stand out in the general logging field apart from Schlumberger: Western Atlas Logging Services, which was called Atlas Wireline Services (ex-Dresser Atlas) and Halliburton Logging Services (ex-Gearhart and incorporating Welex). B.P.B. Wireline, originally the logging arm of British Plaster Board, is an additional, small player.

Table 1.2 Principal uses of open-hole wireline logs.

Chapter	Uses	General geology: Lithology – general	Unusual Lithology: Volcanics	Unusual Lithology: Evaporites	Mineral identification	Correlation: stratigraphy	Facies depositional env.	Reservoir geology: Fracture identification	Over-pressure identification	Geochemistry: Source rock identification	Maturity	Petrophysics: Porosity	Permeability	Shale volume	Fm. water salinity	Hydrocarbon saturation	Gas identification	Seismic: Interval velocity	Acoustic impedance
3	Temperature								–		+						–		
4	Caliper							–					–						
5	SP					–	–						–	+	*				
6	Resistivity	–		–		–	–		+	+	+	+	–		–	*	–		
7	Gamma ray	–	–	+	–	–	–			+				+					
7	Spectral GR	–	–	+	+	–	–	–		+				+					
8	Sonic	+		–		–		+	+	+		*					–	*	*
9	Density	+	–	–	–		–	+	–	+		*					–		*
9	Photoelectric	+	–	–	+														
10	Neutron	+	–	–	–		–			–		*		–			–		
12	Dipmeter					–	–												dip
13	Image logs	–			–	–	–	+					+			+			dip

- (Essentially) qualitative use
+ Semi-quantitative and quantitative uses
* Strictly quantitative

1.8 Well-log interpretation and uses

The accepted user of the well log is the petrophysicist. His interest is strictly quantitative. From the logs, a petrophysicist will calculate porosity, water saturation, moveable hydrocarbons, hydrocarbon density and so on, all the factors related to quantifying the amount of hydrocarbons in a reservoir for estimates of reserves. The Society of Professional Well Log Analysts (SPWLA), the principal society of log interpreters, is mainly composed of petrophysicists.

Reservoir rocks, however, comprise perhaps only 15% of a typical well, and of this 15% only a small percentage actually contains hydrocarbons. The petrophysicist is therefore not interested in 85% or more of the well logs recorded. The exploration geologist, in contrast, should be interested in 100% of well logs, as the amount of geological information they contain is enormous.

The geophysical measurements made during logging are sensitive, accurate and characteristic of the formation logged. However, to those familiar with the aspect of rocks as seen at outcrop, the geophysical signatures of this selfsame rock in the subsurface are impossible to imagine. To an experienced geological analyst of well logs, the reverse is true. A formation that he can instantly identify on the logs, down to the nearest metre, he is hard put to find, even tentatively, at outcrop.

In the following pages it is intended to relate the outcrop more closely to the wireline, geophysical well log. Logs can and should be interpreted in terms meaningful at outcrop. They contain as much information, even sometimes more, than the outcrop, but can be studied conveniently on a small desktop or computer screen.

1.9 This book – content and aims

Table 1.2 shows the logs considered in this book and their principal applications, both geological and geophysical. The applications have been divided into qualitative, semi-quantitative and strictly quantitative. Seismic and petrophysical applications are generally, by necessity, quantitative or semi-quantitative: geological applications, by default, usually qualitative. This should not be. A log sample set of over 100,000 values for a typical well of 2000 m represents an enormous *quantitative database*. Statistical, quasi-quantitative and of course purely quantitative methods applied to this digital log database bring precision to *geological* interpretation. So this book is concerned with qualitative and, wherever possible, the more quantitative methods of *geological log interpretation*.